

# New experimental limit on the Pauli Exclusion Principle violation by electrons

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## Abstract

The Pauli Exclusion Principle (PEP) is one of the basic principles of modern physics and, even if there are no compelling reasons to doubt its validity, it is still debated today because an intuitive, elementary explanation is still missing, and because of its unique stand among the basic symmetries of physics. The present paper reports a new limit on the probability that PEP is violated by electrons, in a search for a shifted  $K_\alpha$  line in copper: the presence of this line in the soft X-ray copper fluorescence would signal a transition to a ground state already occupied by 2 electrons. The obtained value,  $\frac{1}{2}\beta^2 \leq 4.5 \times 10^{-28}$ , improves the existing limit by almost two orders of magnitude.

*Key words:* symmetrization principle, identical particles, tests of quantum field theories, anomalous atomic transitions, X rays, CCD

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## 1 Introduction

The Pauli Exclusion Principle (PEP) is a consequence of the spin-statistics connection [1] and plays a fundamental role in our understanding of many physical and chemical phenomena, from the periodic table of elements, to the electric conductivity in metals, to the degeneracy pressure, which makes white dwarfs and neutron stars stable, just to cite few ones. Although the principle has been spectacularly confirmed by the number and accuracy of its predictions, its foundation lies deep in the structure of quantum field theory and has defied all attempts to produce a simple proof, as nicely stressed by R. Feynman [2].

Given its basic standing in quantum theory, it seems appropriate to carry out precise tests of the PEP validity and, indeed, in the last fifty years, several experiments have been performed to search for possible small violations [3,4,5,6,7,8]. Often, these experiments were born as by-products of experiments with a different objective (e.g. dark matter searches, proton decay, etc..), and most of the recent limits on the validity of PEP have been obtained for nuclei or nucleons.

Concerning the violation of PEP for electrons, Greenberg and Mohapatra [9] examined all experimental data which could be related, directly or indirectly, to PEP, up to 1987. In their analysis they concluded that the probability that a new electron added to an antisymmetric collection of  $N$  electrons might form a mixed symmetry state rather than a totally antisymmetric state is  $\leq 10^{-9}$ . In 1988, Ramberg and Snow [10] drastically improved this limit with a dedicated experiment, searching for anomalous X-ray transitions, that would point to a small violation of PEP in a copper conductor. The result of the experiment was a probability  $\leq 1.7 \times 10^{-26}$  that a new electron circulating in the conductor would form a mixed symmetry state with the already present copper electrons.

We have set up an improved version of the Ramberg and Snow experiment, with a higher sensitivity apparatus [11]. Our final aim is to lower the PEP violation limit for electrons by at least 4 orders of magnitude, by using high resolution Charge-Coupled Devices (CCD) as soft X-rays detectors [12], and decreasing the effect of background by a careful choice of the materials and sheltering the apparatus in an underground laboratory.

In the next sections we describe the experimental setup, the outcome of a preliminary measurement performed in the Frascati National Laboratories (LNF) of INFN in 2005, along with a brief discussion on the results and the foreseen future improvements in the Gran Sasso National Laboratory (LNGS) of INFN.

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## 2 The VIP experiment

The idea of the VIP (VIolation of the Pauli Exclusion Principle) experiment was originated by the availability of the DEAR (DAΦNE Exotic Atom Research) setup, after it had successfully completed its program at the DAΦNE collider at LNF-INFN [13]. DEAR used Charge-Coupled Devices (CCD) as detectors in order to measure exotic atoms (kaonic nitrogen and kaonic hydrogen) X-ray transitions. CCD's are almost ideal detectors for X-rays measurement, due to their excellent background rejection capability, based on pattern recognition, and to their good energy resolution (320 eV FWHM at 8 keV in the present measurement).

### 2.1 Experimental method

The experimental method, originally described in [10], consists in the introduction of new electrons into a copper strip, by circulating a current, and in the search for X rays resulting from the  $2p \rightarrow 1s$  anomalous radiative transition that occurs if one of the new electrons is captured by a copper atom and cascades down to the 1s state already filled by two electrons of opposite spin. The energy of this transition would differ from the normal  $K\alpha$  transition by about 300 eV (7.729 keV instead of 8.040 keV) [14], providing an unambiguous signal of the PEP violation. The measurement alternates periods without current in the copper strip, in order to evaluate the X-ray background in conditions where no PEP violating transitions are expected to occur, with periods in which current flows in the conductor, thus providing “fresh” electrons, which might possibly violate PEP. The fact that no PEP violating transitions are expected to be present in the measurement without current is related to the consideration that any initial conduction electron in the copper that was in a mixed symmetry state with respect to the other copper electrons, would have already cascaded down to the 1s state and would therefore be irrelevant for the present experiment. The rather straightforward analysis consists in the evaluation of the statistical significance of the normalized subtraction of the two spectra, with and without current, in the energy region where the PEP violating transition is expected.

### 2.2 The VIP setup

The VIP setup consists of a copper cylinder, 4.5 cm in radius, 50  $\mu\text{m}$  thick, 8.8 cm high, surrounded by 16 equally spaced CCD's [15]. The CCD's are at a distance of 2.3 cm from the copper cylinder, grouped in units of two chips vertically positioned. The setup is shown in Fig. 1. The chamber is kept at

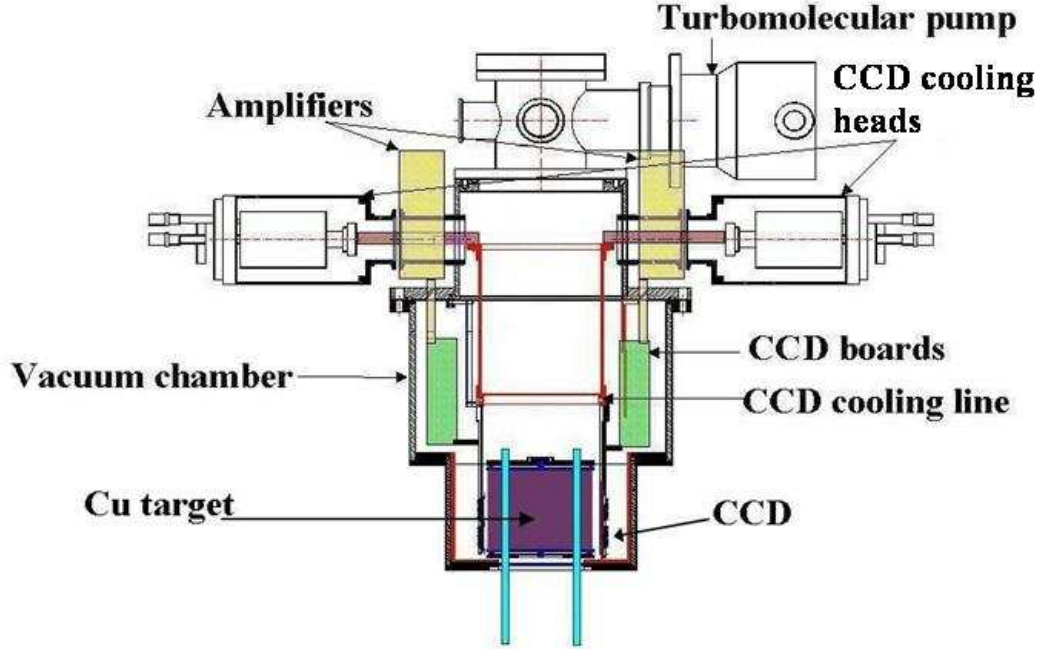


Fig. 1. The VIP setup. All elements of the setup are identified in the figure.

high vacuum to minimize X-ray absorption and to avoid condensation on the cold surfaces. The copper target (the copper strip where the current flows and new electrons are injected from the power supply) is at the bottom of the setup. The CCD's surround the target and are supported by cooling fingers that start from the cooling heads in the upper part of the chamber. The CCD readout electronics is just behind the cooling fingers; the signals are sent to amplifiers on the top of the chamber. The amplified signals are read out by ADC boards in a data acquisition computer.

More details on the CCD-55 performance, as well as on the analysis method used to reject background, can be found in [16]

### 2.3 Measurements

The measurements reported in this paper have been performed in the period 21 November - 13 December 2005, at the Frascati National Laboratories of INFN, Italy.

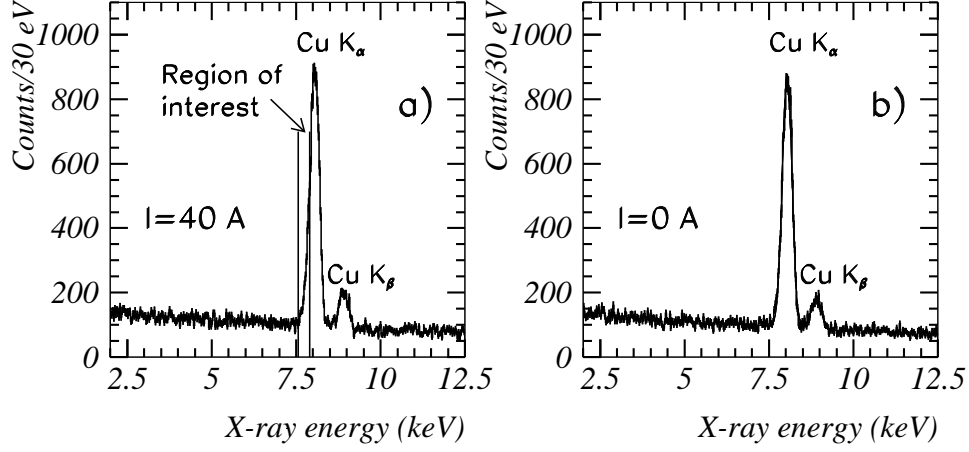


Fig. 2. Energy spectra for the VIP measurements: a) with current ( $I=40$  A); b) without current ( $I=0$ ).

Two types of measurements were performed:

- 14510 minutes (about 10 days) of measurements with a 40 A current circulating in the copper target;
- 14510 minutes of measurements without circulating current,

where CCD's were read-out every 10 minutes.

The two resulting X-ray spectra are shown in Figure 2 a), with circulating current, and b), without current. The spectra refer to 14 CCD's (out of 16), due to noise problems in the remaining 2.

### 3 PEP-violating X-ray spectrum

In order to obtain the number of X-rays due to the possible PEP violating transitions, the spectrum without current was subtracted from the one with current.

The resulting subtracted spectrum is shown in Figure 3 a) (whole energy scale) and b) (a zoom on the region of interest). The region of interest, from 7.564 to 7.894 keV, is defined by the CCD energy resolution (320 eV FWHM) at the  $K_\alpha$  copper transition (8.04 keV), with an additional uncertainty of 10 eV, to account for the theoretical uncertainty in the calculation of the PEP violating transition energy. The numbers of X rays in the region of interest were:

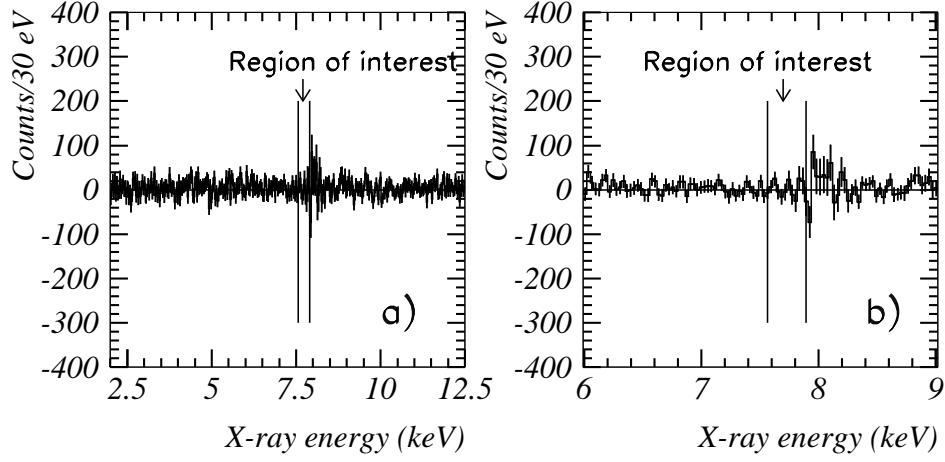


Fig. 3. The subtracted spectrum: current minus no-current, giving the limit on PEP violation for electrons: a) whole energy range; b) expanded view in the region of interest (7.564 - 7.894 keV). No evidence for a peak in the region of interest is found.

- at  $I=40$  A:  $N_X = 2721 \pm 52$ ;
- for  $I=0$  A:  $N_X = 2742 \pm 52$ ;
- for the subtracted spectrum:  $\Delta N_X = -21 \pm 73$ .

### 3.1 Determination of the PEP violation probability limit

For the parametrization of the results in a Pauli principle violating theory, we use the notation of Ignatiev and Kuzmin [17], which has been incorporated in the paper of Greenberg and Mohapatra [9]: even though the model of Ignatiev and Kuzmin has been later shown to be incompatible with quantum field theory [18], the parameter  $\beta$  that measures the degree of PEP violation has stuck and is still found in the literature, also because it is easy to show that it is related to the parameter  $q$  of quon theory, by the relation:  $(1 + q)/2 = \beta^2/2$  [19] (in quon theory,  $-1 \leq q \leq 1$ , where  $q = -1$  corresponds to fermions and  $q = 1$  corresponds to bosons, so that here  $q$  must be close to -1 and  $(1 + q)/2$  must be very small, because we are dealing with electrons). Moreover, we used this parametrization for an easy comparison of our results with the previous Ramberg and Snow ones [10], since the same has been used in that paper. In [17] a pair of electrons in a mixed symmetry state has the probability  $\beta^2/2$  for the symmetric component and  $(1 - \beta^2/2)$  for the usual antisymmetric one. The parameter  $\beta^2/2$  is related, then, to the probability that an electron violates PEP (see also [20] for further details). To determine the experimental

limit on  $\beta^2/2$  from our data, we used the same arguments of Ramberg and Snow, to compare the results. The number of electrons that pass through the conductor, which are new for this conductor, is:

$$N_{new} = (1/e)\Sigma I\Delta t. \quad (1)$$

where  $e$  is the electron electric charge,  $I$  is the current intensity and  $\Delta t$  represents the time duration of the measurement with current on. Each new electron will undergo a large number of scattering processes on the atoms of the copper lattice. The minimum number of these internal scattering processes per electron, defined as  $N_{int}$ , is of order  $D/\mu$ , where  $D$  is the length of the copper electrode (8.8 cm in our case) and  $\mu$  is the mean free path of electrons in copper. The latter parameter is obtained from the resistivity of the metal. We assume that the capture probability (aside from the factor  $\sim \beta^2/2$ ) is greater than  $\frac{1}{10}$  of the scattering probability.

The acceptance of the 14 CCD detectors and the probability that an X ray of about 7.6 keV, the energy of the possible anomalous transition generated in the copper target, is not absorbed inside the copper itself, were evaluated by a Monte Carlo simulation of the VIP setup, based on GEANT 3.21. This probability turns out to be 2.1%. Moreover, a CCD efficiency equal to 48% for a 7.6 keV X ray was considered. All these factors built up the so called *geometric factor* ( $\sim 1\%$ ).

The number of X rays generated in the PEP violating transition,  $\Delta N_X$ , is then related to the  $\beta^2/2$  parameter by:

$$\begin{aligned} \Delta N_X &\geq \frac{1}{2}\beta^2 N_{new} \frac{1}{10} N_{int} \times (\text{geometric factor}) \\ &= \frac{\beta^2(\Sigma I\Delta t)D}{e\mu} \frac{1}{20} \times (\text{geometric factor}) \end{aligned} \quad (2)$$

Then, for  $\Sigma I\Delta t = 34.824 \times 10^6$  C,  $D = 8.8$  cm,  $\mu = 3.9 \times 10^{-6}$  cm,  $e = 1.602 \times 10^{-19}$  C, we get

$$\Delta N_X \geq 4.9 \times 10^{29} \times \frac{\beta^2}{2}. \quad (3)$$

The difference of events between the measurements with and without current, reported in the previous Section, is  $\Delta N_X = -21 \pm 73$ . Taking as a limit of observation three standard deviations, we get for the PEP violating parameter:

$$\frac{\beta^2}{2} \leq \frac{3 \times 73}{4.9 \times 10^{29}} = 4.5 \times 10^{-28} \text{ at } 99.7\% \text{ CL.} \quad (4)$$

We can interpret this as a limit on the probability of PEP violating interactions between external electrons and copper atoms:  $\frac{1}{2}\beta^2 \leq 4.5 \times 10^{-28}$ . We have thus improved the limit obtained by Ramberg and Snow by a factor about 40.

## 4 Conclusions and perspectives

The paper reports a new measurement of the PEP violation limit for electrons, performed by the VIP Collaboration at LNF-INFN. The search of a tiny violation was based on a measurement of PEP violating X-ray transitions in copper, under a circulating 40 A current. A new limit for the PEP violation for electrons was found:  $\frac{1}{2}\beta^2 \leq 4.5 \times 10^{-28}$ , lowering by almost two orders of magnitude the previous one [10].

We shall soon repeat the measurement in the Gran Sasso-INFN underground laboratory, at higher integrated currents. From preliminary tests, it appears that the X-ray background in the LNGS environment is a factor 10-100 lower than in the Frascati Laboratories. A VIP measurement of two years (one with current, one without current) at LNGS, to start in Spring 2006, will then bring the limit on PEP violation for electrons into the  $10^{-30}$ - $10^{-31}$  region, which is of particular interest [21] for all those theories related to possible PEP violation coming from new physics.

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